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HIGH-ALTITUDE COOLING

V - COWLING AND DUCTING

By S. Katzoff

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Langley Field, Va.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

HIGH-ALTITUDE COOLING

V - COWLING AND DUCTING

By S. Katzoff

SUMMARY

A discussion is given of the variations with altitude of the air-volume requirements of the carburetor and the various cooling elements, and the effects of these variations on duct design for high-altitude airplanes are shown. The fundamental principles in the design of efficient duct inlets, expanding passages, and outlets are presented, with special reference to the avoidance of flow separation or of compressibility effects; and data are given to show the magnitude of the effects discussed and to provide design criterions.

INTRODUCTION

It is shown in other papers of this series (references 1 to 4) that, with increasing altitude, there is a general increase in the volume of air handled within the airplane and a simultaneous decrease in the pressures available for effecting its flow. Efficient ducting is clearly essential if the necessary quantities of air are to flow under the influence of the available pressures. Faulty design has a direct effect on the attainable altitude, because of either excessive loss of ram in the carburetor scoop, failure to provide the necessary cooling, or reduction in the power available for climb due to the increase in the power required to maintain flight.

The purpose of this paper is to summarize the effects of altitude on air-flow requirements, to point out the resulting effects on the design of ducts for high-altitude airplanes, and to discuss the general principles of efficient duct design. The fundamental principles in the design of duct inlets, expanding passages, and outlets are presented and some quantitative data are given to show the magnitude of the effects discussed and to provide design criterions.

SYMBOLS

D	diameter of duct
g	acceleration of gravity
h	altitude
Δh	altitude difference
H	total pressure
L	length of duct
p	static pressure
Δp	static-pressure increment
q	dynamic pressure
Q	volume rate of flow of cooling air
r	radius of bend (to center line)
V	airspeed
β	angle of bend
ρ	mass density of air

Subscripts:

o	free stream
i	inlet

VARIATION OF AIR-FLOW REQUIREMENTS WITH ALTITUDE

A summary of the altitude problem is contained in figure 1, which shows the approximate variation with altitude of the volume of air required for the carburetor and for cooling the air-cooled engine, the oil cooler, the ethylene-glycol radiator, and the intercooler. For comparison, the approximate variation with altitude of the flight speed for the climb and for the high-speed conditions at constant engine output is also shown in figure 1.

The figure shows, for example, that at 40,000 feet the volume of air taken into the carburetor duct is four times the volume of air taken in at ground level, while the high speed of the airplane is only 1.5 times the high speed at ground level. The pattern and the nature of the flow into a given duct will be quite different for the two conditions (fig. 2). A carburetor duct that is optimum for low altitudes is obviously far from satisfactory at high altitudes; in fact, at 40,000 feet the losses resulting from separation at the inlet and the extremely high duct velocities would correspond to a loss of at least 3000 feet of ram. This remarkably high figure results from the reduced density in two ways:

(1) Pressure losses are roughly proportional to the dynamic pressure. In the case of the carburetor duct, since ρV is constant for constant power, $\rho V^2/2$ is inversely proportional to ρ.

(2) The altitude difference Δh corresponding to a given pressure loss $-\Delta p$ is given approximately by the equation

$$\Delta h = \frac{-\Delta p}{\rho g}$$

that is, Δh is also inversely proportional to ρ. The intercooler duct offers the most extreme example of variation of air-flow requirement with altitude, for, in typical supercharger operation, the intercooler may not be needed at all up to 10,000 feet, above which its air-flow requirement varies similarly to that shown for the carburetor. The ethylene-glycol radiator and the oil-cooler ducts will, however, be approximately satisfactory for all altitudes up to 40,000 feet because the variation of airplane speed approximately matches the variations of air-flow requirements, so that the patterns of the flow into them will not have to change with altitude. The problem presented by the air-cooled engine appears from figure 1 to be similar to but not quite so unfavorable as that presented by the carburetor; the inlet problem in the case of the engine appears, however, only when a large spinner is used.

It will be clear from the foregoing discussion that particular attention must be given to the duct systems in the early layouts of a high-altitude airplane. Since pressure losses are proportional to the local dynamic pressure, it is desirable to maintain low velocities in the ducts insofar as such velocities are compatible with the various other design requisites. A general increase in the size of ducts will result and some increase in the airplane volume may be necessary in order to accommodate them.

SOME FUNDAMENTAL PRINCIPLES OF DUCT FLOW

Boundary-Layer Separation

The retarded layers of low-energy air that flow along solid boundaries, such as duct walls and fuselage skin, present the fundamental difficulties in maintaining streamline flow. Inasmuch as these layers have a momentum deficiency relative to the main flow, they tend to come to a stop under the influence of the static-pressure rise associated with any deceleration of the main flow. Opposing this stoppage is the transfer of momentum from the main flow by means of viscosity or the turbulent interchange of air masses between the main flow and the boundary layer; and this transfer of momentum will serve to maintain the flow if the pressure rise is gradual. The main consideration of streamline design is then the avoidance of pressure rises so steep that the boundary layer will stop and cause the flow to separate from the surface.

Flow seperation at a point may induce separation over an extended region beside and behind this point or, in other cases, may so reduce the energy of the flow as to cause separation at some point farther downstream. For these reasons, it is not always possible to estimate the increase in drag or, in general, the loss of performance that may result from improper design at any particular point. Precise design criterions can accordingly be given only in certain cases and relatively few quantitative data have been presented in the following sections. Experience has, however, shown that the principles here discussed generally suffice for the design of satisfactory ducts and that there is seldom need to sacrifice these principles as a compromise with other design requirements.

Inlets

Some typical inlet types are shown in figure 3. These inlets are characterized by different types of flow and accordingly have different design criterions.

The flow into the inlet of the typical carburetor duct or rear underslung cooling duct (fig. 3(b)) has the fuselage boundary layer on the inner wall. Although it is, in general, desirable for inlet velocities to be low, a limit is set by the presence of this boundary layer, which will cause the flow to separate at the inlet if excessive deceleration is attempted (fig. 4). An inlet velocity of 0.5 to 0.6 of the flight speed is generally as low as can be permitted if such separation is to be avoided (reference 5). When the aspect ratio - that is, the ratio of width to height - of the opening is low, the high pressure in front of the inlet may move a large part of this boundary layer to the sides (fig. 5) and thereby alleviate the danger of separation. In such a case, the permissible inlet-velocity ratio may be less than 0.5; consistent quantitative data on this effect are, however, lacking. The typical front underslung duct (fig. 3(a)) is also more favorable than the rear underslung type because the front underslung duct has only a relatively thin boundary layer at the inlet; somewhat reduced inlet velocities have been used at such ducts without separation.

A further reason for limiting the inlet velocity is that, for very low inlet-velocity ratios, it becomes impossible to avoid high velocities over the lip, with the resulting danger either of separation just back of the minimum pressure region or of formation of a shock wave at high flight speeds. Figure 6 (from reference 6) shows, for example, some pressure distributions over the lip of a carburetor inlet with different inlet velocities. With an inlet-velocity ratio of 0.6 the critical Mach number for this inlet, as calculated from the height of the negative-pressure peak, will be about 0.68, which corresponds to a speed of about 460 miles per hour at 40,000 feet. Since the flow over the lip becomes more favorable with higher inlet velocities, the best compromise for a high-speed, high-altitude airplane may be to use a higher inlet velocity. It is advantageous in general to place such inlets where the field of the airplane has already reduced the local velocity, as at the nose or under the wing. Since figure 6 shows more pronounced negative-pressure peaks at the lower inlet-velocity ratios, the flow over the lip might be expected to be most critical at the lower altitudes where, owing to the increased air density, the inlet-velocity ratio is reduced. Actually, because of the reduced airplane speed and the increased speed of sound, the flow over the lip is less critical at the lower altitudes.

The cowling and large-spinner arrangement (fig. 3(f)) produces an inlet essentially similar to the type just discussed. Tests of such designs have also indicated that inlet-velocity ratios of about 0.5 are most efficient (reference 7).

The flow into a wing duct (fig. 3(c)) is not subject to the boundary-layer difficulties of the flow into an underslung duct; however, a certain instability of the flow is found to occur when the inlet velocity is less than 0.30 to 0.35 of the flight speed. For this reason, the inlet-velocity ratio cannot be reduced below this range. Actually, owing to the fact that a large inlet would cause high velocities over the nose and would, in general, spoil the aerodynamic characteristics of the wing, the usual inlet-velocity ratios are somewhat above this range. Considerable care must be taken in locating a wing-duct inlet. If the inlet is placed too low, the internal flow will, at low angles, separate from the upper lip just within the inlet (fig. 7(a)). If the inlet is placed too high, the internal flow will separate from the lower lip in climb and the external flow will separate over the upper lip at high angles of attack and thereby induce a premature stall (fig. 7(b)). An example of a satisfactory wing inlet is shown in figure 3(c). For wings of sections much different from the one shown, approximately the same arrangement relative to the mean camber line should be maintained. The rotation of the slipstream introduces a further complication by increasing the local angle of attack on the side of the upgoing propeller blade and decreasing the local angle of attack on the side of the downgoing blade. A wing-duct inlet behind the upgoing propeller blade should be between the inlets of figures 3(c) and 7(a).

The flow into an NACA C cowling (fig. 3(e)) is similarly without a boundary layer at the inlet. Nevertheless, owing to the flow instability that results from excessive inlet area and the interference of the hub and the blade shanks and of such elements as the propeller governor or the distributor, the total pressure of the cooling air at the cylinder baffles seldom exceeds $0.8q_o$. At the higher angles of attack, as in climb, the inlet flow is particularly poor because the air enters mainly at the bottom with no flow or even reverse flow near the top; the total pressures in front of the upper cylinders are especially low (generally about $0.6q_o$) for these conditions. The NACA C cowling is also unfavorable to the attainment of high speeds because the high speed of the flow over the nose reduces the critical Mach number to about 0.63 for the low angles of attack and to about 0.55 for the climb attitude. A negative inclination of the cowling axis would be helpful in this respect for an airplane designed to reach high altitudes.

In the NACA D_S cowling (fig. 3(f)) the use of a large spinner to increase the inlet-velocity ratio to about 0.5 not only stabilizes the flow and improves the uniformity at high angles of attack but also reduces the local speeds over the nose. Owing to the rapid expansion between the small inlet and the cylinders, the internal flow may, however, be relatively poor; but, for a careful design, the total pressures at the cylinders will be over $0.90q_o$, which is appreciably higher than for the NACA C cowling. The long-nose engine requires the use of a more gradual expansion between the inlet and the cylinders and is hence much more favorable with respect to the internal flow (reference 8). Propeller cuffs, if designed for thrust, can increase the total pressure at the cylinders by $0.1q_o$ and can also make the pressure distribution more nearly uniform at the higher angles of attack. A fan in the inlet (fig. 3(g)) serves to improve the uniformity still further, even with inlet-velocity ratios as low as 0.25 and seems, furthermore, to improve the duct expansion back of it.

The fuselage nose inlet (fig. 3(d)) has found application in certain special designs. The minimum inlet-velocity ratio consistent with stable and uniform flow into the inlet and with low velocities over the nose will mainly depend on the size of the opening relative to the maximum cross section of the fuselage. For example, the optimum inlet-velocity ratio for the design shown in figure 3(d) is about 0.20 (reference 9).

Inlet designs have usually not provided any adjustment of inlet shape to take care of variations in relative flow velocities accompanying variations in flight conditions. Where some effort is made in the design to provide ducts that will be efficient at all altitudes and for all flight conditions, it may become desirable to provide for variable inlets or for ducts having inlets that are opened only above certain altitudes. Perhaps the simplest compromise for a liquid-cooled engine is to use a common air intake and expanding duct placed either under or at the front of the fuselage or nacelle. The relatively small variation with altitude in the requirements of the ethylene-glycol radiator and of the oil cooler would tend to minimize the effect of the large variation of the carburetor and the intercooler requirements. For an air-cooled engine, combining the oil-cooler inlet duct with the intercooler and the carburetor inlet ducts should similarly help to alleviate the problem; whereas an NACA D cowling with inlet opening designed for 40,000 feet altitude would be acceptable at low altitudes in spite of the low inlet-velocity ratio, especially as there will probably be a blower in the inlet. For high-speed airplanes, it will probably be necessary for the inlet-velocity ratios at high altitudes to be greater than the values here indicated as optimum, in order to avoid harmful compressibility effects in the flow over the nose.

Expanding Ducts

Inasmuch as the velocity at the inlet is generally too high to use at the cooling unit, an expanding passage must be interposed. Here again the sensitivity of the boundary layer restricts the permissible rate of expansion. In the case of an underslung duct, since undepleted air enters on the lower wall, the flow along this wall could withstand a considerable expansion in a relatively short distance without separating. The flow on the upper wall, however, includes the thick fuselage boundary layer and will separate unless the expansion is very gradual. For example, some calculations for a rear underslung radiator duct on a typical pursuit airplane indicated that, with an expansion ratio of 2.3:1, a duct length of 8 or 10 feet would be necessary to prevent separation on the upper surface; whereas 2 or 3 feet would be adequate to prevent separation on the lower surface. The wing duct can, under ideal conditions, have smooth flow on both upper and lower walls and can hence permit a rapid expansion. Rapid expansion is also permissible in a rear underslung duct if the fuselage boundary layer is peeled off into a separate duct and passed around the cooling unit (fig. 8). A somewhat similar result is obtained with a duct that has a protruding inlet (fig. 9); the external drag of such an inlet has, however, been found to be high. In nearly ideal expansions of the types just discussed, the expansion losses are very small - of the order of 2 or 3 percent of the dynamic pressure at the inlet.

It is essential, for good flow, to keep obstructions such as pipes or structural members out of ducts, or at least away from their narrowest parts, because local separations caused by such obstructions may induce separation over an extended area and spoil the entire flow of the duct.

The losses of total pressure that result from separation in an expanding duct depend on a number of factors, for example, the amount of expansion that has occurred before the separation point and the size of the dead-air space that is formed. The order of magnitude of the losses is indicated in figure 10 (from reference 10), which shows results for expansions in channels having thick boundary layers on the walls. For the flow in a typical rear underslung duct with a thick boundary layer on one wall, experience has indicated that the curve for the rectangular duct generally underestimates the losses and that minimum losses occur with expansion angles somewhat less than 10°.

It has become customary in the design of ducts where the flow along at least one wall is questionable to restrict the expansion angle to between 6° and 10°. Although these angles may still be too large to prevent separation in some cases, such design will usually restrict the resulting pressure losses to a minimum. Where rapid expansion cannot be avoided, the bell-shaped expanding duct (fig. 11) is advantageous because the first and most important part of the expansion is efficiently performed at a small angle; and the presence of the resistance - that is, the cooling element - at the end of the passage permits a somewhat increased expansion rate in the final stage (reference 11).

In other cases, subdividing the passage by vanes into two or more passages of smaller expansion angle has been found advantageous. With regard to such use of vanes, it must be emphasized that the subdivision of a passage into several sections does not insure that the flow will be distributed in the desired proportions among them, especially when a thick boundary layer flows into one of the passages. The analysis of the flow in such cases simply follows by Bernoulli's equation and by the requirement that, at the rear of the vanes, the adjacent layers of air have the same static pressure (reference 5). The correct design is indicated in figure 12; a rear vane, essentially a continuation of the front one, restricts the exit of the lower passage, which increases the velocity at that point and correspondingly decreases the static pressure so that, when equal air quantities flow in the two passages, the static pressures at the exits of the passages are equal.

Outlets

An efficient outlet passage is a smoothly converging duct that opens downstream. (See fig. 12.) The losses in such a passage are negligible because the negative pressure gradient serves to prevent separation. In spite of the essential simplicity of such flow, however, flagrant disregard of the principles of good design may result in such large outlet losses as not only to increase considerably the airplane drag but even to prevent the exit of the required quantity of cooling air. Examples of such designs are those that include the exhaust collector ring just within the opening (fig. 13(a)), those that require a sudden change in direction at the outlet (figs. 13(b) and (c)), and those that permit the air to find its way out of wheel wells or other incidental openings.

The necessary area of the exit opening is determined as the ratio of the volume of cooling air per second to the exit velocity. The volumes required for the various purposes have been discussed elsewhere; these volumes must, however, be corrected for the reduction in density that occurs in passing through the cooling unit. The exit velocity is determined by the exit dynamic pressure, that is, by the difference between the total pressure of the air behind the cooling unit and the static pressure at the opening.

The total pressure at the outlet is estimated as the difference between the total pressure at the inlet and the internal losses. Of the internal losses, the diffuser losses and the losses in the cooling unit have already been discussed. In estimating the total pressure at the inlet, the increased dynamic pressure in the slipstream must be taken into account, together with the fact that the part of the entering air which constitutes the fuselage boundary layer has a mean total-pressure deficiency of about 0.12 of the external dynamic pressure. The losses in the converging exit passage are negligible under ideal conditions; for the typical air-cooled engine installation, however, the accumulation of pipes and wires behind the engine offers appreciable resistance to the flow and will account for an additional pressure loss of perhaps 5 percent of the pressure loss through the engine itself (reference 12).

The static pressure, for an exit like that of figure 12, is simply the static pressure of the external flow in its vicinity. For most positions along the fuselage, the static pressure will be very nearly equal to the free-stream static pressure. At the skirt of a cowling the static pressure will be less than this value by about $0.1q_o$; at the upper surface of a wing, it will be less by $0.1q_o$ to $1.0q_o$, depending on the chordwise location and the angle of attack; at the lower surface of a wing, it may be higher by $0.1q_o$ to $0.5q_o$, also depending on the chordwise location and the angle of attack. A cowl flap extended at an angle of 15° to 30° to the surface provides within the flap opening a static pressure less than the static pressure of the external flow by about 0.4 to 0.6 of the local external dynamic pressure (references 12 and 13), depending on the flap chord. The use of flaps in climb thus provides an important increase in the pressure drop available for cooling, an effect which is further amplified if the flap is located in the slipstream. Figure 14 shows a tentative curve, based on data from cowling tests, for the variation of the induced negative pressure with flap angle. In the case of a flap at the rear of an underslung duct, the effect is probably somewhat less than that shown in the figure, owing to the small aspect ratio of the flap. Flap angles greater than 30° do not generally serve to increase the flow, possibly because of the poor duct-outlet shape corresponding to such flap angles. In general, for efficient design the flap opening must be the minimum area of the outlet passage (fig. 15).

A wing duct having its outlet on the upper wing surface, about 0.5 to 0.6 chord back of the leading edge, tends to adjust automatically the flow quantity with speed because of the relative increase with lift coefficient of the negative pressure at the outlet. The adjustment is, however, slight; in cases where satisfactory adjustment has been found, the explanation is that the inlet was so designed that there were large inlet losses at low angles of attack and satisfactory inlet flow at high angles of attack.

Except for an outlet like that of figure 12, the effective outlet area is not in general clearly defined. For example, results with outlets like that of figure 16 indicate that the inertia of the external flow has an appreciable effect in reducing the exit flow; that is, if the exit dynamic pressure is taken as the difference between the internal total pressure and the external static pressure, it is necessary to use an orifice coefficient of 0.5 to 0.9, depending on the ratio of the exit velocity to the velocity of the external flow. The higher values apply to the more usual case in which the two velocities are nearly equal.

A flap will generally be provided at the exit in order to permit adjustment of the flow for the different operating conditions. The lowest curve of figure 17 shows, for example, the calculated variation with altitude of the exit area needed for the ethylene-glycol radiator duct of the typical pursuit airplane of reference 3 at high speed. The exit static pressure has been assumed equal to the free-stream static pressure because the necessary adjustment can probably be attained with small flap angles. If, however, the exit pressure for the climb condition were also free-stream static pressure, the corresponding outlet area would become excessive (uppermost curve of fig. 17). The negative pressure induced by extending the outlet flap accordingly becomes an essential factor in increasing the exit velocity and thereby keeping the necessary outlet area within practical limits. The middle curve of figure 17 shows the outlet area required in climb when the flap angle is such as to induce a pressure reduction of about 0.45 of the dynamic pressure in the slipstream.

For any design in which drag reduction is an important consideration, it will be well to keep the internal losses so low that a flap angle no greater than 12° to 15° is needed to provide the necessary exit area and pressure. The drag increases rapidly with larger flap angles; in a typical case, with cowl flaps extended 30°, the total cooling-drag increment corresponded to five times the internal pump work $-Q\,\Delta p$. In such cases the use of a blower, even though not actually essential to supply the necessary pressure for cooling, may be justified.

With short-span exit flaps, a large part of the drag is associated with the flow around the two flap tips. Closing the flap ends (fig. 18) effects considerably reduction of the drag without changing the pumping effectiveness of the flap.

Bends

The flow in a bend is characterized by high velocity at the inner corner and low velocity at the outer corner (fig. 19). There is, accordingly, a region of rising static pressure on the inner wall downstream of the bend and on the outer wall upstream of the bend. The flow on the inner wall is the more critical and separation from the inner wall generally occurs just beyond sharp bends. Increasing the radius of curvature or increasing the aspect ratio of the bend serves to reduce bend losses. An approximate formula from reference 14 for the pressure loss at a bend (excluding the skin-friction loss) is

$$\frac{-\Delta p}{q} = abc$$

where

$-\Delta p$ loss of total pressure in bend

q mean dynamic pressure in channel

a,b,c factors given by figure 20 as functions of angle of bend, radius of curvature, and aspect ratio, respectively

Such formulas, however, can hardly be general inasmuch as the flow is influenced by the Reynolds number and the nature of the boundary layer on the walls. Other studies (reference 15) indicate somewhat higher losses.

If it is not practical to use either a large radius of curvature or a high aspect ratio at the bend, the loss at the bend may nevertheless be reduced to about $0.25q$ by a cascade of turning vanes (fig. 21). Circular arcs of about 80° curvature with a spacing of about 0.4 of their chord and placed at an angle of 45° to 48° to the upstream flow have been found satisfactory. Some rounding of the leading edge is advisable to make the adjustment less critical.

The loss at sharp-cornered elbows in circular channels is shown in figure 22.

The losses at bends frequently constitute the main part of the losses in short ducts of nearly uniform cross section. For longer ducts, the skin friction at the walls also becomes an important factor. The estimation of this loss will seldom be accurate because it depends on the type of construction. An approximate formula for the pressure drop along a uniform duct having the usual manufacturing irregularities is

$$\frac{-\Delta p}{q} = 0.025\frac{L}{D}$$

CONCLUSIONS

1. The increase in air requirement with increase in altitude is greatest for the intercooler and least for the oil cooler, the order being: intercooler, carburetor, air-cooled engine, ethylene-glycol radiator, oil cooler.

2. Consistent adherence to the principles of streamline flow in duct design is essential for efficient operation of a high-altitude airplane.

3. For fuselage ducts or, in general, where a developed boundary layer enters on one side of a duct inlet, the ratio of inlet velocity to flight velocity should be at least 0.5 to 0.6 for good inlet flow. For a wing duct the ratio may be as low as 0.35.

4. Increased inlet-velocity ratios may be required at high speeds and high altitudes in order to avoid critical speeds over the nose of the inlet.

5. The NACA D cowling gives higher pressures at the engine and also has a higher critical Mach number than the NACA C cowling.

6. The difficulties associated with the wide variation of the air requirements with altitude for the intercooler and the carburetor may be alleviated by using a common air intake and expanding duct for the carburetor, intercooler, ethylene-glycol radiator, and oil cooler.

7. For a wing duct under ideal conditions, rapid expansion between the inlet and the cooling element is permissible. For an undersiung duct the expansion must be gradual.

8. Dividing vanes are useful in permitting a rapid expansion in a short space, but only under certain conditions.

9. No total-pressure losses occur in a reasonably well-designed outlet.

10. The effective outlet area is generally less than the geometric outlet area, especially for a flush outlet.

11. Flap deflections of 15° and 30° reduce the outlet static pressure by about 0.5 and 0.8 of the external dynamic pressure, respectively. The larger flap deflections, however, cause large increments of drag.

12. The loss of total pressure at a sharp bend in a duct may exceed the dynamic pressure of the flow in the duct.

13. Bend losses will be small if the section aspect ratio is at least 2 and the radius of curvature is at least twice the depth of the channel or if curved guide vanes are used in the bend.

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REFERENCES

1. Silverstein, Abe: High-Altitude Cooling. I - Résumé of the Cooling Problem. NACA ARR No. L4I11, 1944.

2. Williams, David T.: High-Altitude Cooling. II - Air-Cooled Engines. NACA ARR No. L4I11a, 1944.

3. Nielsen, Jack N.: High-Altitude Cooling. III - Radiators. NACA ARR No. L4I11b, 1944.

4. Rubert, K. F.: High-Altitude Cooling. IV - Intercoolers. NACA ARR No. L4I11c, 1944.

5. Katzoff, S.: The Design of Cooling Ducts with Special Reference to the Boundary Layer at the Inlet. NACA ACR, Dec. 1940.

6. Nelson, W. J., and Czarnecki, K. R.: Wind-Tunnel Investigation of Carburetor-Air Inlets. NACA ARR, Feb. 1942.

7. Valentine, E. Floyd: Preliminary Investigation Directed toward Improvement of the NACA Cowling. NACA ARR, April 1942.

8. Silverstein, Abe, and Guryansky, Eugene R.: Development of Cowling for Long-Nose Air-Cooled Engine in the NACA Full-Scale Wind Tunnel. NACA ARR, Oct. 1941.

9. Becker, John V.: Wind-Tunnel Tests of Air Inlet and Outlet Openings on a Streamline Body. NACA ACR, Nov. 1940.

10. Gibson, A. H.: On the Flow of Water through Pipes and Passages Having Converging or Diverging Boundaries. Proc. Roy. Soc. (London), ser. A, vol. 83, no. 563, March 2, 1910, pp. 366-378.

11. McLellan, Charles H., and Nichols, Mark R.: An Investigation of Diffuser-Resistance Combinations in Duct Systems. NACA ARR, Feb. 1942.

12. Molloy, Richard C., and Brewster, James H., III: New Research on the Cowling and Cooling of Radial Engines. NACA ARR, May 1942.

13. Stickle, George W., Naiman, Irven, and Crigler, John L.: Pressure Available for Cooling with Cowling Flaps. NACA Rep. No. 720, 1941.

14. Abramovich, G.: Fluid Motion in Curved Channels. From Collection of Reports on Industrial Aerodynamics and Fan-Construction, Rep. No. 211 (text in Russian), Trans. Central Aero-Hydrodyn. Inst. (Moscow), 1935, pp. 97-151.

15. Henry, John R.: Design of Power-Plant Installations. Pressure-Loss Characteristics of Duct Components. NACA ARR No. L4F26, 1944.

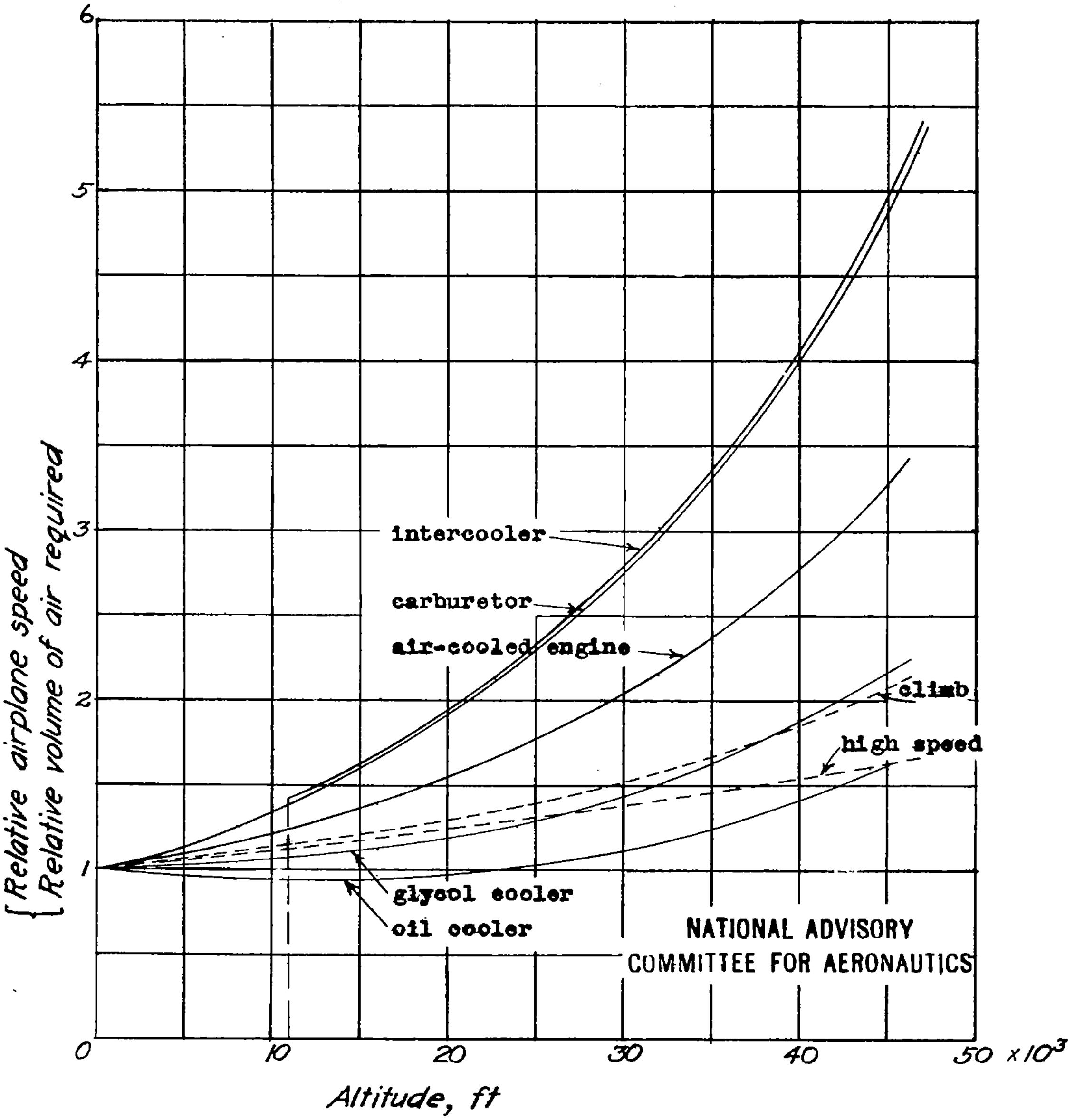
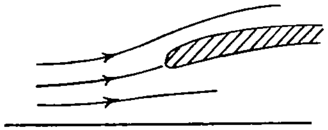
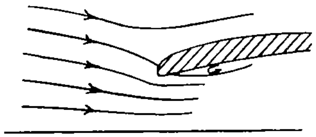


Figure 1.— Variation of air requirements compared with variation of flight speed.



(a) Low altitude.



(b) High altitude.

Figure 2.- Comparison of inlet-flow patterns for low and high inlet-velocity ratios corresponding to a carburetor duct at low and high altitudes.

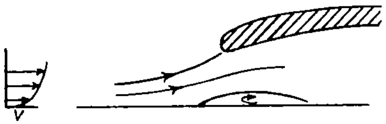


Figure 4.- Separation and reversal of the flow at an oversize duct inlet.

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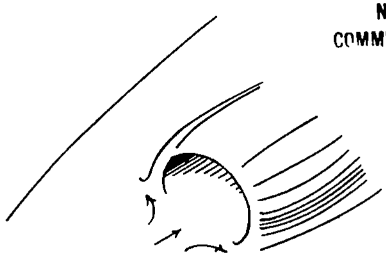
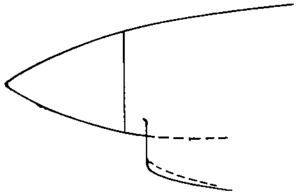
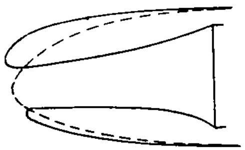


Figure 5.- Streamlines near the surface showing the outward displacement of the boundary layer before an inlet of low aspect ratio.

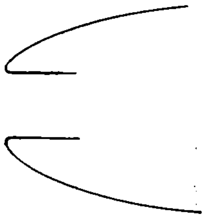


(a) Front underslung duct inlet.

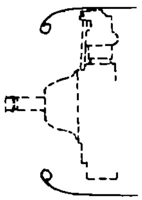
(b) Rear underslung duct inlet.



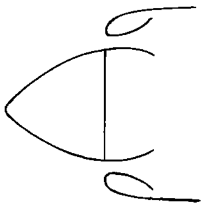
(c) Wing duct inlet.



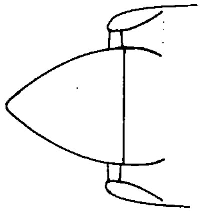
(d) Fuselage nose inlet.



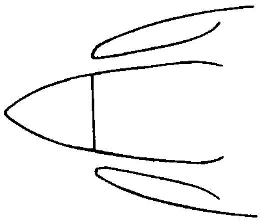
(e) NACA C cowling.



(f) NACA D_S cowling, short-nose engine.



(g) NACA D_F cowling with blower.



(h) NACA D_L cowling, long-nose engine.

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Figure 3. - Inlet types.

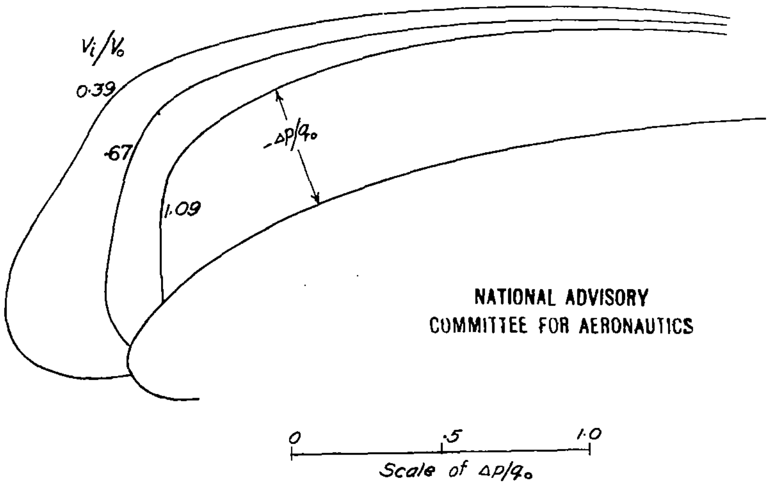

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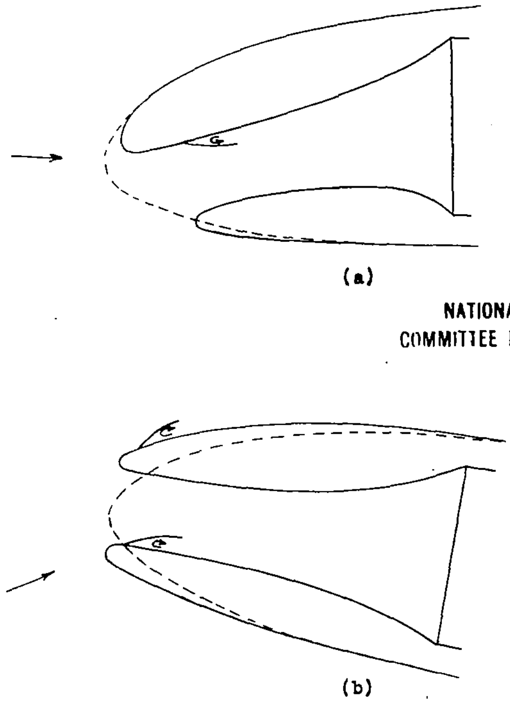
Figure 6.-Effect of inlet-velocity ratio on pressures over the nose of a carburetor-duct inlet. From reference 6.



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(a) Low inlet, with separation at low angles of attack.
(b) High inlet, with separation at high angles of attack.

Figure 7. - Types of poor flow at wing duct inlets.

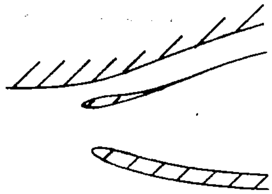

Figure 8. - Inlet of a rear underslung duct having a separate passage for the boundary layer.

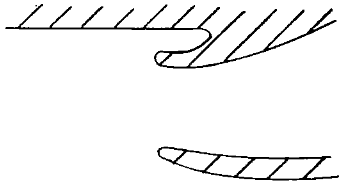

Figure 9. - Protruding inlet of an underslung duct.

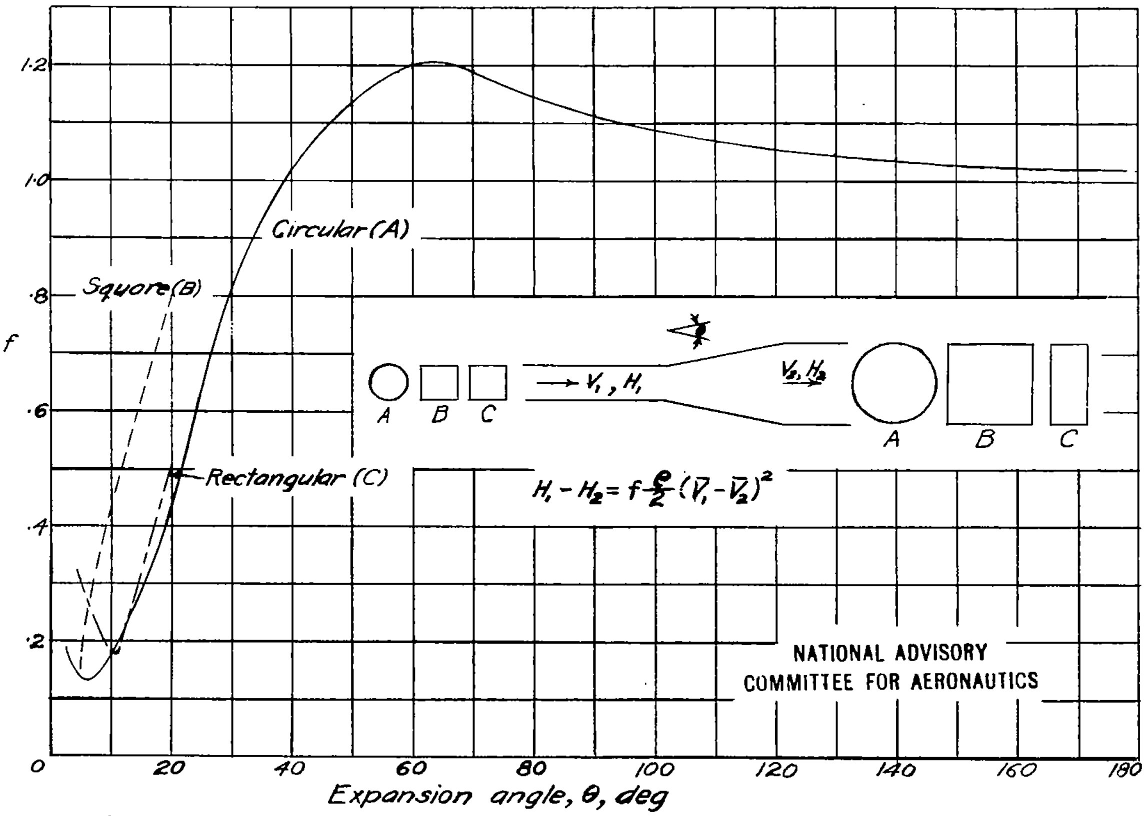

Figure 10.– Loss of total pressure in an expanding duct with a thick boundary layer on the wall at the inlet. From reference 10.

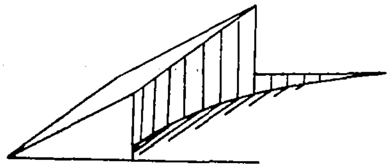

Figure 18.- Exit flap with closed ends.

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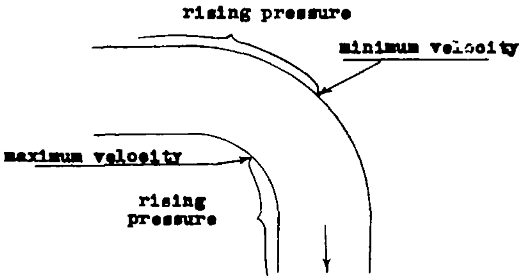

Figure 19.- Diagram showing where separation may occur in a bend.

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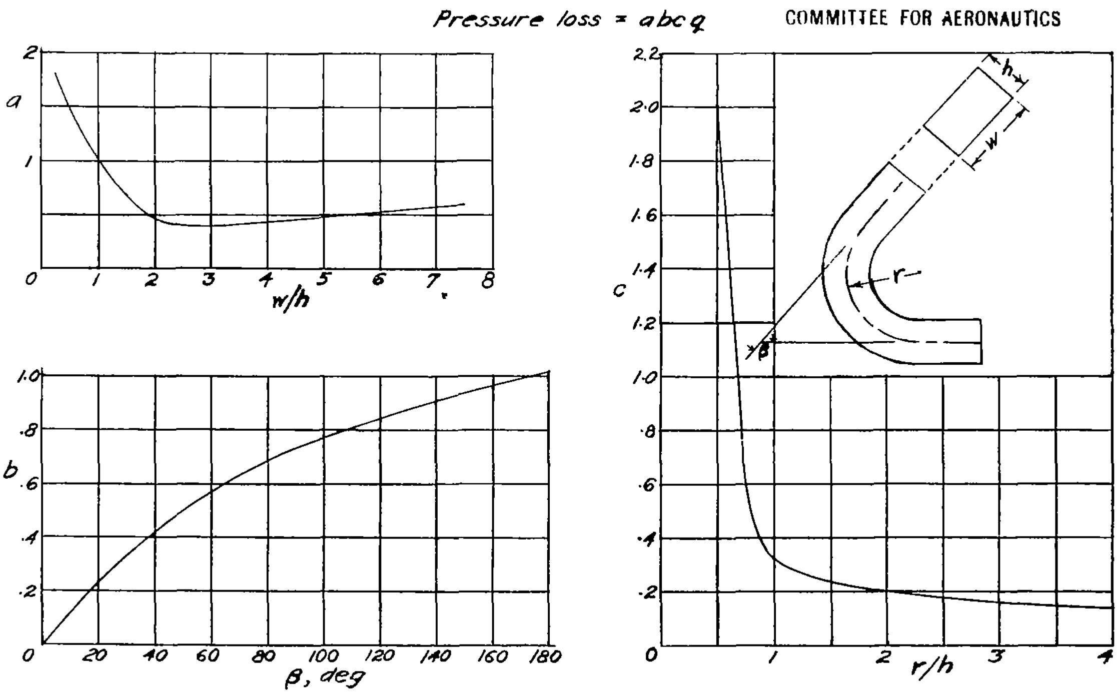

Figure 20.— Curves for the pressure loss in flow around a bend, excluding friction loss.

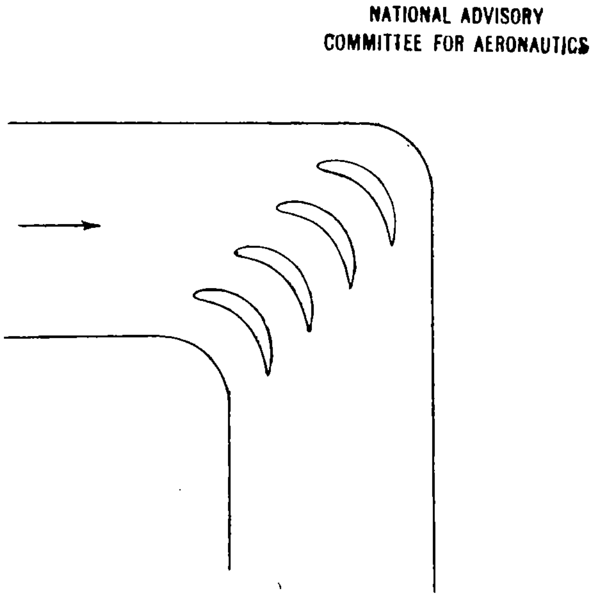

Figure 21.— Bend with vanes.

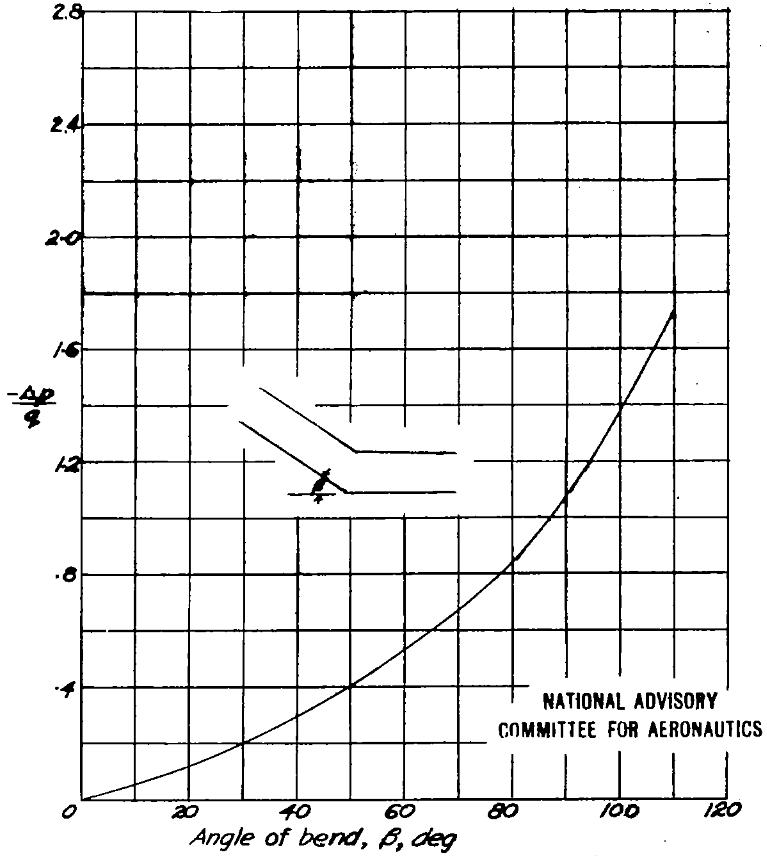

Figure 22.— The pressure loss at a sharp-cornered elbow in a circular duct.

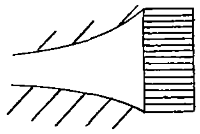

Figure 11. - The bell-shaped expanding duct.

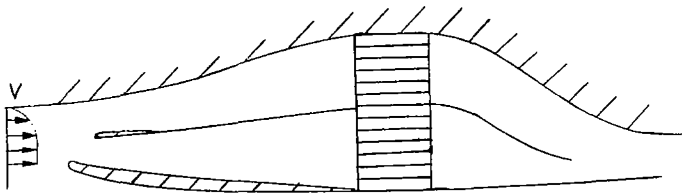

Figure 12. - A duct with a rear vane to equalize the flow when a boundary layer enters the upper section.

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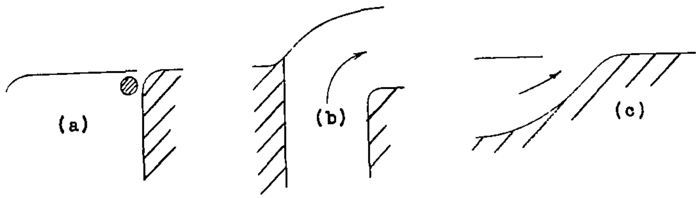

Figure 13.- Examples of poor exits.

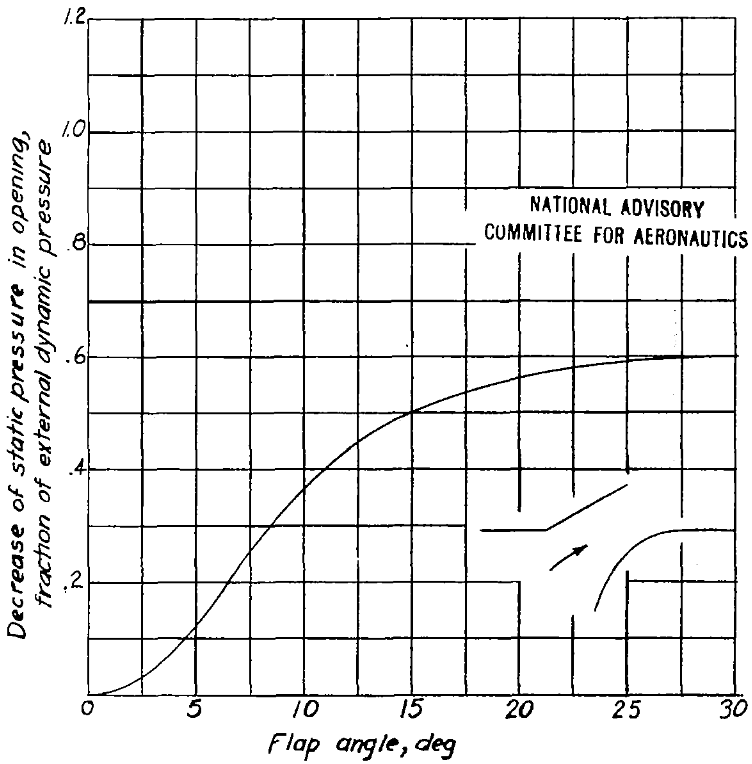

Figure 14.- Effect of flap deflection on static pressure in the exit.

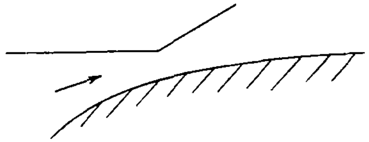

Figure 15.- Flap opening greater than minimum section of outlet passage.

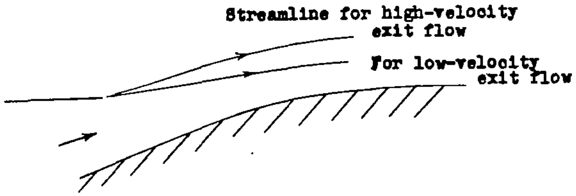

Figure 16.- The contraction of the flow after leaving a flush exit.

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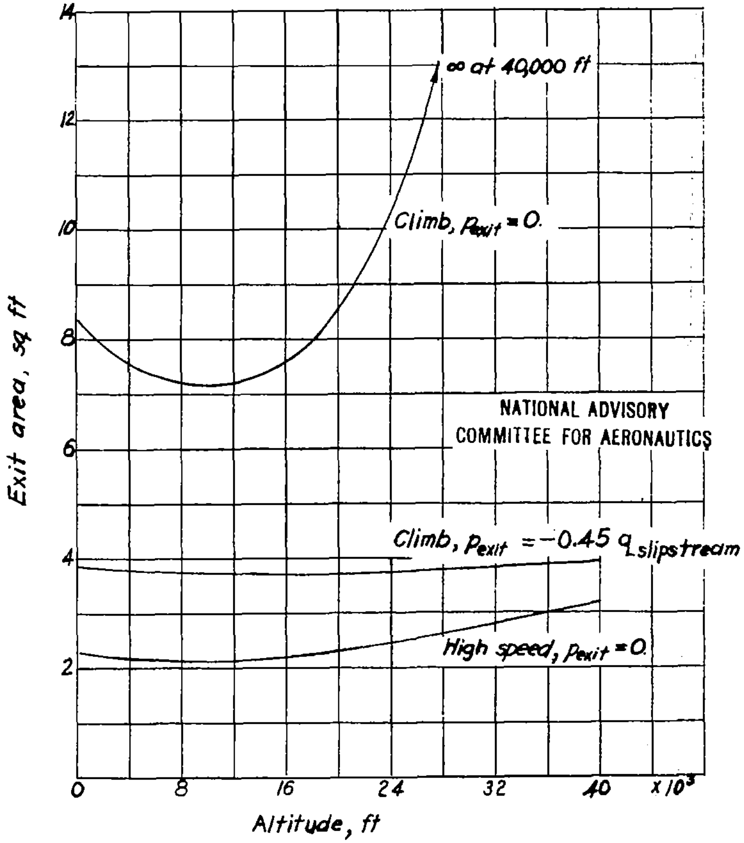

Figure 17.- Variation of exit area with altitude for high-speed and climb. Ethylene-glycol radiator duct.

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